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Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes

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Abstract

Carbon emissions from drained peatlands converted to agriculture in South-East Asia (i.e., Peninsular Malaysia, Sumatra and Borneo) are globally significant and increasing. Here, we map the growth of South-East Asian peatland agriculture and estimate CO_2 emissions due to peat drainage in relation to official land-use plans with a focus on the reducing emissions from deforestation and degradation (REDD+)-related Indonesian moratorium on granting new concession licences for industrial agriculture and logging. We find that, prior to 2010, 35% of South-East Asian peatlands had been converted to agriculture, principally by smallholder farmers (15% of original peat extent) and industrial oil palm plantations (14%). These conversions resulted in 1.46–6.43 $GtCO_2$ of emissions between 1990 and 2010. This legacy of historical clearances on deep-peat areas will contribute 51% (4.43–11.45 $GtCO_2$) of projected future peatland CO_2 emissions over the period 2010–2130. In Indonesia, which hosts most of the region's peatland and where concession maps are publicly available, 70% of peatland conversion to agriculture occurred outside of known concessions for industrial plantation development, with smallholders accounting for 60% and industrial oil palm accounting for 34%. Of the remaining Indonesian peat swamp forest (PSF), 45% is not protected, and its conversion would amount to CO_2 emissions equivalent to 0.7%–2.3% (5.14–14.93 Gt) of global fossil fuel and cement emissions released between 1990 and 2010. Of the peatland extent included in the moratorium, 48% was no longer forested, and of the PSF included, 40%–48% is likely to be affected by drainage impacts from agricultural areas and will emit CO_2 over time. We suggest that recent legislation and policy in Indonesia could provide a means of meaningful emission reductions if focused on revised land-use planning, PSF conservation both inside and outside agricultural concessions, and the development of agricultural practices based on rehabilitating peatland hydrological function.

KEYWORDS
CO_2 emissions, Peat swamp forest, REDD+, South-East Asia

1 | INTRODUCTION

Peat swamp forests (PSFs), the natural vegetation cover found on peatlands in Peninsula Malaysia, Southern Thailand, Sumatra, and Borneo (hereafter South-East Asia), once covered 21% of the region. However, large swathes have been cleared for agriculture, leading to widespread wildfires, species extinction, and globally significant carbon emissions (Chisholm, Wijedasa, & Swinfield, 2016; Hooijer et al., 2010; Moore et al., 2013; Page, Siegert, Rieley, & Boehm, 2002; Posa, Wijedasa, & Corlett, 2011; Turetsky et al., 2015; van der Werf et al., 2009; Wijedasa, Posa, & Clements, 2015). Fires used to convert PSF to agriculture have exposed millions of people to prolonged haze and caused multibillion dollar losses (Chisholm et al., 2016; Field et al., 2016; Gaveau et al., 2014). Regional inventories of peatland land-use change have documented increasing contributions to conversion of 20% to 50% by industrial plantations (i.e., large-scale plantations of oil palm, *Acacia*, or other industrial species) and small-scale agriculture (hereafter smallholders) (Miettinen & Liew, 2010a; Miettinen, Shi, & Liew, 2016; Miettinen, Hooijer, Shi et al., 2012). However, there is uncertainty in the degree to which PSF conversion and emissions have been directly sanctioned by governments via land-use concessions, considering that PSF conversion, including by smallholders, occurs both inside and outside of concessions. The land-use status and relative contributions of industrial plantations and smallholders to PSF conversion and emissions must be clarified if recently announced measures to reduce peatland emissions through bans on further industrial conversions and increased peat restoration (President of Indonesia, 2011b, 2016) are to be effective.

Conversion of peatland to agriculture requires drainage to change water-logged swamp conditions to dry, aerated soil suitable for crop production (Comeau et al., 2016; Hirano et al., 2012; Hooijer, Silvius, Wösten, & Page, 2006; Hooijer et al., 2010; Wijedasa et al., 2016). Drainage promotes aerobic microbial decomposition of the peat, which leads to globally significant CO_2 emissions and fluvial losses of ancient carbon deep below the surface (Drösler et al., 2014; Evans et al., 2014; Moore et al., 2013). Hooijer et al. (2010) estimated that peatland drainage-related emissions alone were equivalent to 1.3%–3.3% of annual global greenhouse gas emissions across all of South-East Asia (including Papua New Guinea) in 2010. This estimate has recently been updated for Peninsular Malaysia, Sumatra, and Borneo to be 1.6% of global fossil fuel emissions (Miettinen, Hooijer, Vernimmen, Liew, & Page, 2017). By 2020, emissions due to industrial plantation growth on regional peatlands are predicted to increase two- to threefold relative to 2010 (Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016).

Prior to the COP21 climate-change summit in Paris, South-East Asian countries declared commitments to reduce carbon emissions, particularly from peatlands. Indonesia—which contains 85% of the region's peatlands and from which 63% of national emissions arise from land-use change and fires concentrated on peatlands—declared a target of 29% reduction in national emissions by 2030 compared to the business-as-usual scenario (Republic of Indonesia, 2016). Most of this reduction would be achieved through improved land-use and spatial planning, sustainable forest management, and the restoration of degraded ecosystems (Republic of Indonesia, 2016). The Indonesian moratorium (Republic of Indonesia, 2016) is a key element of Indonesia's emission-reduction plan and illustrative of its commitment to reduce emissions from land use, land-use change, and forestry (LULUCF). First proposed to facilitate a $1-billion bilateral partnership to prepare Indonesia for a global reducing emissions from deforestation and degradation (REDD+) scheme (United Nations & Framework Convention on Climate Change (UNFCCC), & Bonn, 2009), the moratorium prohibits new concessions for industrial agricultural plantations and logging in primary forests and peatlands (President of Indonesia, 2011b, 2016; Sloan, Edwards, & Laurance, 2012). The moratorium in peatlands was relatively ambitious, subsuming all but the shallowest of peatlands not already within concessions, including degraded peat forests and forest-agricultural mosaics. It served to demarcate the maximum extent of industrial plantation conversion and forest exploitation by allowing industrial conversion and exploitation only within concessions granted as of early 2011. Notably, the moratorium does not address smallholder PSF conversion or seek to retain hydrologically integral peat domes across the patchwork of PSF fragments inside and outside of concessions. This is important because peatlands are made up of hydrological units, where protected PSF spanning only part of a peat dome may still experience drainage and CO_2 emissions due to drainage-based conversion elsewhere in the dome (Hooijer et al., 2010; Nagano et al., 2013).

Despite the global significance of regional peatland emissions and recent declarations to stem them, previous estimates have not assessed the degree to which agriculture conversions have occurred inside or outside government-sanctioned agriculture concessions. An important distinction between industrial plantations and smallholders is that the latter are not legally confined by government concessions and the legal or illegal extent of their activities often goes unrecorded in land-use maps (Chisholm et al., 2016; Uryu et al., 2008). The result has been uncertainty in the relative and absolute impact of different land uses on PSF conversion and emissions and concordant uncertainty in the utility of land-use plans to stem emissions. Further, projections of land-use change and resultant emissions have simplistically drawn from observations separated by decades, ignoring spatial and temporal variations in conversion rates amongst land uses, peat depths, and regions (Abood, Lee, Burivalova, Garcia-Ulloa, & Koh, 2014; Hooijer et al., 2010; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016) and overlooking nonlinear trends in emissions and peat subsidence (Abood et al., 2014; Busch et al., 2015; Koh, Miettinen, Liew, & Ghazoul, 2011; Miettinen & Liew, 2010a; Miettinen et al., 2017). With the major regional wildfire haze events of 2015 and the COP21 climate-change summit focusing global attention on regional peatland destruction (Wijedasa et al., 2015), there is a critical need for improved estimates of historic and future peatland emissions to ensure effective regional land-use plans.

Here, we map land-cover change over South-East Asian peatlands from 1990 to 2010 and project future PSF conversion in Sumatra and Kalimantan (hereafter Indonesia) under plausible scenarios of agricultural expansion to quantify past and future peat CO_2 emissions due to PSF conversion and drainage accounting for current emission-reduction strategies. We focus on agricultural conversion because it is the greatest driver of peatland loss (Koh et al., 2011; Miettinen, Hooijer, Wang, Shi, & Liew, 2012; Miettinen & Liew, 2010a; Miettinen, Shi, & Liew, 2012; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016). We used Landsat satellite imagery to map agriculture expansion from industrial plantations and smallholders in peat swamps at 30-m resolution over 1990, 2000, 2005, and 2010 and subsequently to project PSF-to-agriculture conversion in Indonesia from 2011 onwards. Projections focus on Indonesia due to the availability of recent spatial data on agricultural and forestry concessions and because it contains 85% of the region's remaining PSF.

Conversion inside industrial agricultural concessions was projected according to historical (2005–2010) rates inside concessions specific to region (Sumatra, Kalimantan) and peat-depth class. Conversion outside concessions was similarly projected at historic rates of smallholder agriculture expansion specific to region and peat depth for all PSF eligible for conversion according to official land-use plans. Finally, we used the IPCC framework of Drösler et al. (2014) and Hooijer et al. (2006, 2010) to estimate historic (1990–2010) and near-current/future (2010–2130) peat CO_2 emissions following agricultural conversion and drainage within current land-use plans. Our emission estimates are conservative because they exclusively consider emissions from peat oxidation arising after agricultural conversion and exclude emissions from unknown amounts of above-ground biomass loss and fires which have recently been estimated to be 0.48 $GtCO_2$ per year (Miettinen et al., 2017). We provide an improved understanding of historically "committed" and likely future peat CO_2 emissions due to agriculture and implicitly evaluate the effectiveness of the Indonesian moratorium and similar schemes in curbing emissions from extensively disturbed peatlands.

2 | MATERIALS AND METHODS

Our methodology entailed four steps. First, we mapped agricultural land use and, secondly, nonagricultural land covers on peatlands for 1990, 2000, 2005, and 2010 using Landsat imagery. Third, we projected the exhaustive conversion of remaining peat swamp forest (PSF). Fourth, we estimated resultant CO_2 emissions from peatlands over 1990–2130. These steps are detailed below.

2.1 | Historic (1990–2010) peatland agricultural conversion

Historic peatland agricultural expansion was mapped over 1990–2010 across all peatlands of South-East Asia (Peninsular Malaysia, Southern Thailand, Sumatra, and Borneo), as delineated by Wijedasa, Sloan, Michelakis, and Clements (2012), by visually interpreting 268 Landsat satellite images and 24 Landsat GeoCover tiles (30-m resolution) (The Global Land Cover Facility, 2011). Four agricultural classes (industrial oil palm plantation, industrial *Acacia* plantation, other industrial plantations, and smallholder agriculture) (Table S4) were mapped for 1990, 2000, 2005, and 2010 following the protocols of Miettinen et al. (Miettinen, Hyer, Chia, Kwoh, & Liew, 2013; Miettinen & Liew, 2010b; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016; Miettinen et al., 2017). We estimated the net aerial changes and rates of expansion of each class over 1990–2000, 2000–2005, and 2005–2010 (Table S1).

2.2 | Creation of a 2010 peatland land-cover map

To project PSF conversion from 2010, we first composed a single land-use/cover map of 2010 spanning all South-East Asian peatlands. This map integrated the four land-use classes of the 2010 agricultural map described above with four land-cover classes of a separate 2010 map of nonagricultural peatlands described below. This integrated land-use/cover map was the basis for projecting PSF conversion in Indonesia from 2010.

We classified all nonagricultural peatlands into four land-cover classes: (i) mature PSF, (ii) secondary/regrowth PSF, (iii) non-PSF mosaic lands, and (iv) bare/urban/burned lands (Table S4). Classes were delineated using a maximum-likelihood supervised classification of Landsat imagery following Wijedasa et al. (2012), with a slight variation on their postclassification image-compositing procedure used to "fill in" cloudy areas in a classified image with data from coincident classified images. The study area covered a total of 58 different Landsat footprints across South-East Asia.

Our revised image-compositing procedure yielded more accurate land-cover maps than those of Wijedasa et al. (2012). The revised procedure entailed three steps. First, classified images were compared to unclassified false-colour Landsat satellite images and classified areas that appeared to accurately reflect the land-cover classes visually interpreted in the false-colour composite were manually demarcated and "clipped" out from each classified image of 2010. Second, clipped extents were ranked according to image date (most recent to least recent) and cloud cover (least cloudy to most cloudy). At last, a cloud-free composite classified image was composed using the highest-ranking clipped extents for each location across all South-East Asian peatlands.

2.2.1 | Accuracy assessment of historical agriculture & 2010 land-use/cover maps

Separate accuracy assessments following methods described by Wijedasa et al. (2012) were realized for the 1990–2010 agricultural land-use maps and the integrated 2010 land-use/cover map. Actual land-use/cover classes were interpreted for 1,160 and 687 randomly distributed points using high-resolution imagery in Google Earth and compared respectively against the 1990–2010 agricultural map and the integrated 2010 land-use/cover map. The Google Earth imagery used was acquired over the same time period as the Landsat imagery. Conducting these assessments separately allowed for the use of additional historical reference data for the 2000s when assessing the 1990–2010 agricultural maps. The accuracy assessments have been discussed in detail in Wijedasa et al. (2012).

Regarding the integrated 2010 land-use/cover map, classification accuracy was especially high for the mature PSF class (92%) but lower for the disturbed/regrowth PSF class (65%) due to partial confusion with the mature PSF class (Table S5). This discrepancy does not undermine our analysis, however, as mature PSF and disturbed/regrowth PSF were considered as one entity in our projection and estimates of historical and future emissions. The overall accuracy of the map was 81.6%. Upon weighting the user's accuracy by the mapped area of each class to account for differences in class extent, the overall classification accuracy was 81.1%.

For the accuracy assessment of the 1990–2010 peatland agricultural land-use maps, 565 of the 687 ground-reference sites surveyed were for the year 2010 with the remaining 122 reference points spread between the years 2000 and 2009 (Table S6). Considering the temporal persistence of agricultural land uses, reference sites of a given year were used to assess the classification accuracy of an agricultural class mapped *on* or *after* that year. For instance, a reference site interpreted using a 2005 Google Earth image would be used to validate an agricultural class mapped locally on or after 2005. The overall classification accuracy of the agricultural maps was 91.4%, with an area-weighted overall classification accuracy of 92.8% (Table S6).

2.3 | Projecting future (2010–2130) land-cover change on indonesian peatland

Our projection of PSF-to-agriculture conversion was realized exclusively for Indonesia because only in Indonesia are recent spatial data on agricultural concession designations available. However, our projection still describes a *regional* scenario, considering that Indonesia contained 85% of remaining PSF in South-East Asia as of 2010.

PSF conversion in Indonesia was projected from 2010 to 2130 following two steps. The first step entailed segmenting remaining PSF as of 2010 (i.e., mature PSF and secondary/regrowth PSF) into different official land-use designations, detailed below (e.g., oil palm concession, protected area). The second step entailed extrapolating historic (2005–2010) agricultural conversion rates specific to each combination of land-use designation, region, and peat depth until all nonprotected PSF of 2010 within a designated area was converted. These steps are elaborated below.

2.3.1 | Segmenting remaining PSF of 2010 by land-use designation

Remnant PSF in 2010 was segmented into subregional zones of relatively homogenous land-use and biophysical characteristics, thus defining the spatial units of our land-use projection. PSF was first segmented by official land-use designation, namely protected areas, the Indonesian moratorium area, smallholder agriculture, and industrial agricultural concessions for oil palm or *Acacia* production. Concessions areas were as delineated by the Indonesian government in 2011 (Ministry of Forestry, 2010). Occasional spatial overlap amongst these oil palm and *Acacia* concessions was resolved by labelling overlapping areas according to the concession designation corresponding to the locally dominant industrial land use. Protected area maps of all nationally designated protected areas were obtained from the World Database of Protected Areas (UNEP/IUCN, 2010). The official fifth Indonesian moratorium map (IMM5) (President of Indonesia, 2011b, 2016; Presidential Working Unit of Supervision, Control and Development, 2013) defines the area over which Indonesia has prohibited new industrial agricultural, logging, and mining concessions. The areas outside of agricultural concessions, protected areas, and the moratorium were considered the domain of smallholder agriculture, officially designated or otherwise. Each of these four land-use designations were in turn further partitioned by region (Sumatra, Kalimantan) and peat-depth class (mapped by Wetlands International; Wahyunto, & Subagjo, 2003; Wahyunto & Subagjo, 2004) to reflect spatial variation in PSF conversion rates. In combination, these land-use designations and partitions thereof provided the basis to describe a plausible scenario of future PSF conversion and conservation presuming that present land-use schemes are fully realized.

2.3.2 | Future conversion of PSF based on historic (2005–2010) agriculture expansion rates

Agriculture conversion of PSF was projected from 2010 at historical (2005–2010) rates specific to each partition of each land-use designation until all PSF therein would be converted. The use of historical rates specific to each partition recognizes distinct local relationships between PSF loss, the land-use designation, and the partitions thereof, for example, hypothetically, slower industrial plantation expansion amongst PSF fragments within deep-peat areas of concessions, or rapid smallholder expansion in undisturbed shallow-peat areas outside of concessions.

It was assumed that future conversion rates within a given partition of a given land-use designation would reflect historical expansion rates of the predominant agricultural class of the partition. Thus, projected conversion rates within a given industrial-concession partition reflected industrial plantation expansion rates within that partition, while projected conversion rates within a given partition outside of concessions reflected historical smallholder expansion rates within that partition. This approach yields conservatively late estimates of the year by which all PSFs are projected to be converted because the locally predominant agricultural land use alone does not account for all PSF conversion within a given partition or land-use designation.

We assumed that PSF within protected areas, logging concessions, and the moratorium area would persist indefinitely because PSF conversion is prohibited within the former three areas while industrial agriculture conversion (including for *Acacia* plantations) is prohibited within the latter. However, peat CO_2 emissions from all such areas are still possible due to partial peat drainage along their peripheries following the agricultural conversion of adjacent peatlands. While Indonesia has renewed its dedication to protecting peatlands and moratorium areas (Ministry of Environment of Indonesia, 2010; President of Indonesia, 2011a; Republic of Indonesia, 2016), smallholder agriculture is not precluded by the moratorium and so it is possible that some moratorium PSF areas may be converted by smallholders in the absence of other protections or enforcement. Our projection of PSF conservation in protected areas, logging, and moratorium areas is therefore probably conservative.

The extrapolation of historical rates of agricultural expansion observed over 2005–2010 was preferable to extrapolating rates over longer historical periods such as 1990–2010 because the dynamics of PSF conversion have changed over time. Whereas Indonesian oil palm expansion rates over 2005–2010 are comparable to those over 1990–2010, expansion rates for *Acacia* plantations and smallholder over 2005–2010 are ~50% greater than for 1990–2010 (Table S1), reflecting in part the Indonesian government's promotion of *Acacia* expansion since the mid-2000s (Verchot et al., 2010). Increasing rates of expansion and recent policy shifts support our choice to project future land-use change according to the relatively recent historical expansion rates for 2005–2010.

We assessed the efficacy of the Indonesian moratorium and protected areas at maintaining PSF integrity given expected PSF conversion in other land-use designations by simulating the potential for passive drainage and emissions from peat oxidization within moratorium and protected areas. All moratorium and protected PSF within 1 km and 2 km of lands converted as of 2010 were considered subject to passive drainage, as per Hooijer et al. (2010), with the expectation of actual drainage decreasing with distance (Table 2). Peat CO_2 emissions from drained PSF were estimated using the IPCC Tier 1 emission factors (Table S7) for drained forests on organic soils (Supplementary Dataset: Summary.xls: IMM5_PassiveDrainageEmissions). However, these emissions were estimated for 2010 only because projecting future emissions due to drainage in protected or moratorium PSF would require a prohibitive degree of precision concerning the location and distribution of future PSF conversion over specific periods.

2.4 | Estimating historical and future CO_2 emissions from peatlands

Peat CO_2 emissions following historical (1990–2010) and future (2010–2130) land-cover change were estimated following the methods of the IPCC framework of Drösler et al. (2014) and Hooijer et al. (2006, 2010), with key refinements. Our methods estimate CO_2 emissions following large-scale peat drainage for agriculture including tree plantations by integrating: (a) our aerial estimates of historical and future agricultural conversion on peatlands (Tables 1, S1, S2), (b) peat-depth maps of Wetlands International (Wahyunto & Subagjo, 2004; Wahyunto & Subagjo, 2003), extended using the original PSF-cover map of Wijedasa et al. (2012), (c) peatland subsidence rates following drainage (to account for the local cessation of emissions once all peat soil has been oxidized) (Couwenberg & Hooijer, 2013; Hooijer et al., 2012; Jauhiainen, Hooijer, & Page, 2012), (d) CO_2 emission rates from peatlands converted to specific agriculture types according to IPCC Tier 1 estimates of emissions due to peat oxidation (CO2-$C_{ON\text{-}SITE}$) (IPCC, 2014), varied by whether they were elevated or not elevated in the initial years postconversion as per Hooijer et al. (2006, 2010), and (e) IPCC Tier 1 estimates for dissolved organic carbon (CO_2-C_{DOC}) (Table S7).

2.4.1 | Peatland emissions

The estimation of emissions entails 18 emission scenarios for each peatland agriculture class (i.e., oil palm, Acacia, smallholder, and other industrial). Each scenario is outlined in Table S8. Divergence amongst these scenarios reflects key variations of three parameters, namely emission factors for peatland conversion, peat subsidence rates, and emission factors for dissolved organic carbon.

The first level of variation is defined by the IPCC emission factors specific to each of our four agriculture land uses. IPCC emission factors entail three potential values or "scenarios" based on a 95% confidence interval around the nominal IPCC emission rate. These values, denoted by CO_2-$C_{ON\text{-}SITE}$ in Table S7, are (*i*) *Upper CI*, in which the upper 95% confidence interval of the IPCC emission factor is used; (*ii*) *IPCC Emission Factor*, in which the IPCC Tier 1 emission factor is used; and (*iii*) *Lower CI*, in which the lower 95% confidence interval of the IPCC emission factor is used.

The second level of variation in our emission scenarios pertains to whether emissions during the first 5 years following PSF deforestation and drainage are elevated or not. In the first such situation, denoted *Scenario 1*, emissions from converted peatland are higher (178 t CO_2 ha^{-1} yr^{-1}) during the first 5 years postconversion, as per Hooijer et al. (2012), after which they are lower, as per the IPCC Tier 1 (Drösler et al., 2014) emission factors, for our specific agricultural land uses (CO_2-$C_{ON\text{-}SITE}$) and dissolved organic carbon (CO_2-C_{DOC}) (Table S7). In contrast, in the alternative situation denoted *Scenario 2*, IPCC Tier 1 emission factors for each of our plantation types on drained organic soils are treated as constant rates from the moment of peatland conversion (Page et al., 2011; Transportation and Climate Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, 2014). Each of these two situations references the specific IPCC Tier 1 emission factor for dissolved organic carbon (CO_2-C_{DOC}) and different types of agriculture (CO_2-$C_{ON\text{-}SITE}$) on drained organic soils (i.e., industrial oil palm, industrial *Acacia* plantations, smallholder agriculture, and other industrial plantations) (Drösler et al., 2014). The emission estimate of the first 5 years post-PSF conversion to agriculture is currently debated in literature (Page et al., 2011; Transportation and Climate Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, 2014). The emissions estimate by Hooijer et al. (2012) remain the only study to measure subsidence and estimate corresponding emissions in the first 5 years post conversion of PSF to agriculture. Similar high initial emissions after drainage were found by Kool, Buurman, and Hoekman (2006) in contexts of peat drainage for illegal logging. While the Kool et al.'s study does not pertain to PSF conversion to agriculture, its value of 109 [CI 57–161] t CO_2 ha^{-1} y^{-1} falls within the range of Scenario 1 here.

The third level of variation is the IPCC Tier 1 emission factor for dissolved organic carbon, which again defines three values based on the 95% confidence interval. These values, denoted CO_2-C_{DOC} in Table S7, are thus (a), Upper 95% confidence interval (4.18 t CO_2 ha^{-1} yr^{-1}); (b), IPCC Tier 1 emission factor (3.01 t CO_2 ha^{-1} yr^{-1}); and (c), lower 95% confidence interval (2.06 t CO_2 ha^{-1} yr^{-1}).

TABLE 1 Peatland area ('000 km^2) converted to different agricultural land uses inside and outside of concessions, 1990–2010, by region

	Sumatra				Kalimantan				Peninsula Malaysia and Thailand				Sarawak, Sabah, and Brunei				TOTAL SE ASIA			
Area ('000 km^2)	1990	2000	2005	2010	1990	2000	2005	2010	1990	2000	2005	2010	1990	2000	2005	2010	1990	2000	2005	2010
OIL PALM[b]	**1.51**	**11.06**	**14.01**	**18.29**	**0.04**	**0.25**	**1.21**	**4.40**	**1.31**	**1.82**	**1.94**	**2.17**	**0.03**	**1.33**	**2.61**	**5.69**	**2.89**	**14.46**	**19.77**	**30.55**
Total concession Area[a]				11.02				20.04												
Industrial oil palm in concession	0.29	3.75	4.68	5.64	0.01	0.07	0.47	1.98												
Smallholder in concession	0.03	0.68	1.15	1.87	0.03	0.31	0.41	0.47												
Total converted	0.32	4.43	5.84	7.51	0.04	0.38	0.88	2.46												
% converted	3%	40%	53%	68%	0%	2%	4%	12%												
Industrial oil palm outside concessions	1.22	7.31	9.33	12.66	0.04	0.18	0.74	2.42												
ACACIA[b]	**0.00**	**1.28**	**5.40**	**8.71**	**0.00**	**0.01**	**0.02**	**0.10**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.29**	**5.41**	**8.81**
Total concession area[a]				20.8				4.25												
Acacia in concession	0.00	0.93	3.72	6.19	0.00	0.01	0.07	0.12												
Smallholder	0.00	0.40	0.66	1.52	0.00	0.01	0.15	0.18												
Total converted	0.00	1.33	4.39	7.70	0.00	0.01	0.22	0.31												
% converted	0%	6%	21%	37%	0%	0%	5%	7%												
Acacia outside concessions	0	0.4	1.7	2.5	0.0	0.0	0.0	0.0												
SMALLHOLDER[b]	**10.46**	**16.83**	**19.67**	**24.62**	**2.73**	**4.02**	**4.81**	**5.67**	**1.01**	**1.48**	**1.77**	**2.04**	**0.27**	**0.44**	**0.68**	**0.78**	**14.47**	**22.76**	**26.94**	**33.21**
Total smallholder—outside concessions	10.43	15.75	17.86	21.33	2.70	3.70	4.25	5.02												
Total smallholder—inside concessions	0.03	1.08	1.81	3.39	0.03	0.32	0.56	0.65												
OTHER INDUSTRIAL PLANTATION	**1.53**	**2.72**	**2.87**	**3.06**	**0.0**	**0.0**	**0.0**	**0.0**	**1.8**	**1.8**	**1.8**	**1.8**	**0.0**	**0.0**	**0.1**	**0.1**	**3.28**	**4.48**	**4.72**	**4.95**
TOTAL	**13.50**	**31.53**	**40.28**	**52.25**	**2.78**	**4.27**	**6.09**	**10.20**	**4.1**	**5.1**	**5.5**	**6.0**	**0.3**	**1.8**	**3.4**	**6.6**	**20.65**	**42.98**	**56.83**	**77.53**

Note. [a]Industrial-concession conversion reflects the combined growth of industrial plantations as well as smallholder agriculture inside concession boundaries. Industrial plantation and smallholder areas are reported separately.

[b]Total regional oil palm area is a combination of industrial oil palm inside and outside of concessions and excludes smallholder extent within concessions. Total regional Acacia area is a combination of industrial Acacia inside and outside of concessions and excludes smallholder extent within concessions. Total regional smallholder area is similarly a combination of smallholder area inside and outside of concessions.

In total, for each of our four agricultural land uses, the three levels of variation discussed above define eighteen emission scenarios. Emissions reported in the main text are typically presented as a range of the absolute lowest and highest emissions defined by these eighteen scenarios. Hereafter, each emission scenario is labelled according to its unique combination of values, following the order and terminology discussed above. For example, the scenario *Upper CI Scenario1a* denotes the combination of the "upper IPCC" emission factors for peatland conversion, "Scenario 1" regarding initially elevated peatland emissions, and value "a" regarding the upper IPCC emission factor for dissolved organic carbon. Similarly, the scenario *IPCC Emission Factor Scenario1a* denotes the combination entailing the nominal IPCC emission factors for peatland conversion and is otherwise the same.

2.4.2 | Peatland subsidence and depth

Peat emissions for a given partition of a given land-use designation were presumed to continue at rates described above from the first-year peatland conversion was observed until all peat soil in the partition was or would be oxidized. This cessation point is a function of the rate at which peatlands subside following peatland conversion as well as the peat depth at the time of conversion. Accordingly, it was necessary to estimate subsidence rates and peat depths in a spatially explicit manner.

For both our emission scenarios (*Scenario 1* and *Scenario 2*), which vary in terms of their emission rates during the first 5 years postconversion, we assumed an elevated subsidence rate of 1.42 m/5 years during the first 5 years following conversion and thereafter assumed a lesser land-use-specific subsidence rate given in Table S9. For smallholder agriculture and other industrial plantations, the lower subsidence rate for oil palm was applied because the literature has not specified subsidence rates specific to these agricultural land uses. These staged subsidence rates reflect measurements of post-conversion elevation to peatlands (Couwenberg, Dommain, & Joosten, 2009; Couwenberg & Hooijer, 2013; Hooijer et al., 2006; Jauhiainen et al., 2012).

Subsidence as well as emissions were averaged over 5-year intervals during 2000–2130 and over the single 10-year interval for 1990–2000, in keeping with the time periods for which historical land change was mapped. For the period 1990–2000, we assumed that all peatlands converted to agriculture by 1990 were emitting and subsiding at the reduced rates. For peatlands converted between 1990 and 2000, we assumed that these peatlands had experienced five initial years of high subsidence rates followed by a further 2.5 years of the reduced subsidence rates. For *Scenario 1*, peatlands converted between 1990 and 2000 were similarly assumed to experience higher emission rates for the first 5 years postconversion, followed by 2.5 years of reduced emission rates.

We estimated the spatial extent of peatlands of various depths by integrating regional Wetlands International (WI) peat-depth maps (Wahyunto & Subagjo, 2004; Wahyunto & Subagjo, 2003) with Wijedasa et al. (2012) map of original regional PSF extent and then correcting for historical (premapping) peatland subsidence. The original PSF map of Wijedasa et al. (2012), which also defines our study extent, integrated historic soil and vegetation maps with Landsat imagery from 1990 to delineate PSF cover prior to the commencement of anthropogenic land-cover change, including shallow areas of peatlands converted prior to the creation of the WI peat-depth maps around the year 2000.

Nominal peat depths in all peatland maps were occasionally adjusted to correct for subsidence that occurred prior to the original delineations of peat depths. Specifically, as the WI depth maps were produced after 2000, they would not account for subsidence following conversion realized before 2000. We corrected for subsidence occurring prior to the WI maps by increasing the depths reported by WI by the estimated subsidence over 1990–2000 wherever peatland was converted over 1990–2000. Where WI did not map depths for peatlands observed in the present study, we conservatively estimated depths at 1 m as per Hooijer et al. (2006, 2010) and again corrected for postconversion subsidence as above. The step-like declining trend in peatland emissions over time (Figure S1) reflects the 0.5-m intervals in peat-depth maps and indicates vast geographical regions of relatively shallow peat ceasing to emit after exhaustive peat CO_2 emissions.

The WI peat-depth maps (Wahyunto & Subagjo, 2004; Wahyunto & Subagjo, 2003) used here probably conservatively estimate actual peat depth at any given point (Jaenicke, Rieley, Mott, Kimman, & Siegert, 2008). While the WI maps have been updated by Ritung, Wahyunto, Sukarman, and Suparto (2011), an overlay and visual comparison of the maps of WI and Ritung et al. (2011) shows that the updated maps for our study area (Sumatra and Kalimantan) are essentially the WI maps less those peatlands that no longer exist due to exhaustive postconversion oxidation and subsidence. Our study already captures these and other instances of peatland disappearance by projecting peatland oxidation and subsidence until such time as the entire peat mass becomes exhausted, as detailed above. Our estimates may be particularly conservative for the case for Malaysia, Southern Thailand, and Brunei, where some greater peat depths have been reported (Anderson, 1964), although no alternative national peat-depth map exists to confirm this generally. We nonetheless emphasize that emissions will be more prolonged and ultimately greater to the degree that actual peat depths are greater than estimated here.

Peatland emissions were compared to cumulative global and national figures from the World Bank (2013). These emissions include carbon dioxide emissions from the burning of fossil fuels and cement manufacture.

3 | RESULTS

3.1 | Drivers of peatland conversion inside and outside government-sanctioned concessions

Our analysis finds that by 2010, PSF had declined to 40% of its original extent, with large variation between countries and regions

(Tables 1, S1 and Figure 1). The decline of original PSF extent in 2010 was greatest in Sumatra (−72%) and Peninsula Malaysia/Thailand (−74%), as compared to the combined regions of Sabah, Sarawak, Brunei (−50%), and Kalimantan (−46%) (Table S2). The remaining PSF is in various states of degradation.

Regionally smallholders have been the principal individual driver of peatland-to-agriculture conversion (Tables 1, S2). Smallholders accounted for 43% of all agricultural conversion of peatland observed by 2010, followed by industrial oil palm plantations at 39%, industrial *Acacia* plantations at 11%, and other industrial plantations at 6% (Table 1). The magnitude of smallholder conversion relative to industrial plantations is contrary to other observations over the same period for Sumatra and elsewhere in South-East Asia (Abood et al., 2014; Lee et al., 2014; Miettinen & Liew, 2010a; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016). Smallholder conversion and emissions have typically been overlooked in favour of more readily detectable industrial agricultural activities (Abood et al., 2014; Miettinen, Wang, Hooijer, & Liew, 2013; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2012; Miettinen et al., 2016). While the extent of smallholder agriculture has more than doubled between 1990 and 2010, its extent relative to that of industrial agricultural land uses (oil palm, *Acacia*, other industrial plantations) has declined due to a sevenfold increase in the latter over the same period (Table 1). The ratio of smallholders to industrial agricultural extent regionally fell steadily from 2.4 in 1990 to 0.7 in 2010 (Table 1).

The relative areas and distribution of industrial plantations, smallholders, and total agriculture conversion correspond poorly with known concessions. In Indonesia, where most regional peatland-to-agriculture conversion occurred and official concession maps are available, 70% of peatlands converted to agriculture occurred outside of known industrial plantation concessions. Outside concessions, smallholders accounted for 60% of peatland conversion while industrial plantations accounted for a surprisingly substantial remainder, with oil palm accounting for 34% and *Acacia* 6%. Inside plantation concessions, smallholders still accounted for a substantial 23% of conversion, followed by industrial oil palm at 42% and *Acacia* at 35% (Table 1). Thus, in Indonesia, smallholders account for most PSF

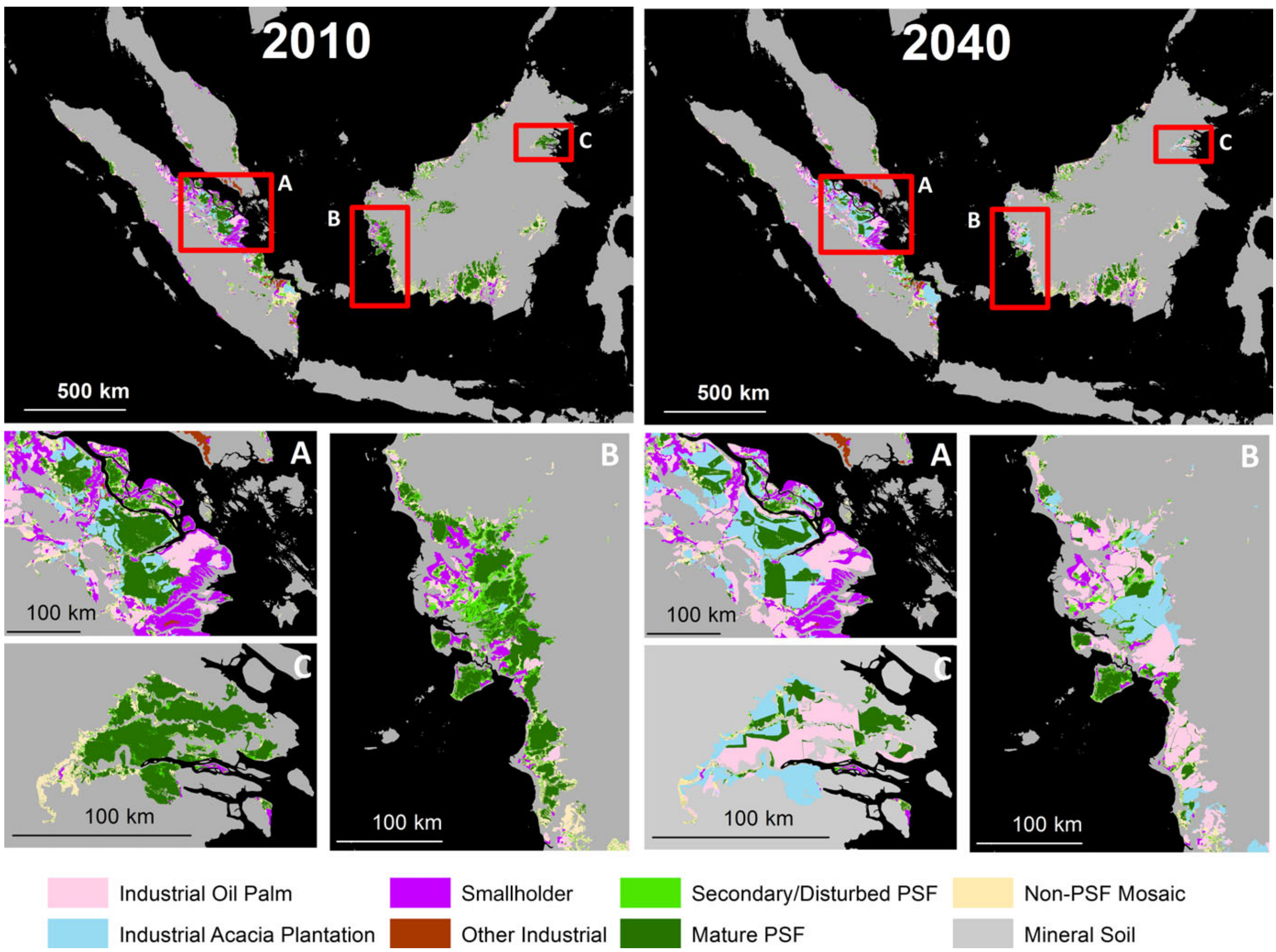


FIGURE 1 Land cover on peatlands in South-East Asia for the years 2010 and 2040 [Colour figure can be viewed at wileyonlinelibrary.com]

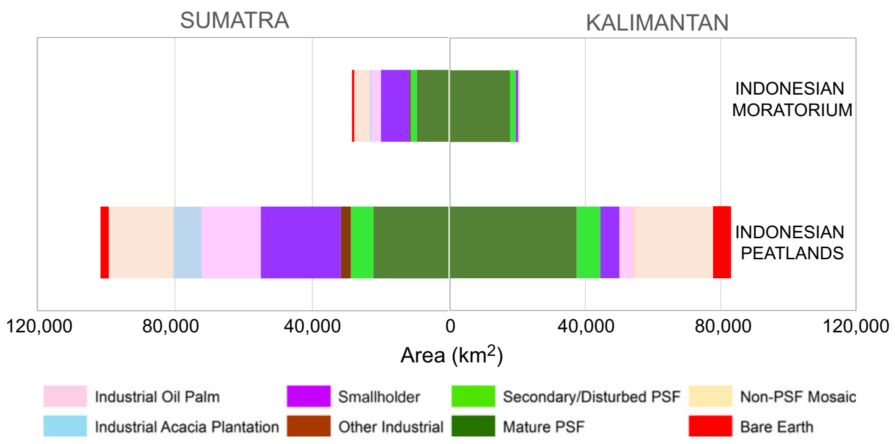


FIGURE 2 Land cover on Indonesian peatlands (excluding West Papua) (bottom) and within the extent of the Indonesian moratorium on new concessions (top), for peatlands defined by the present study. [PSF refers to peat swamp forest] [Colour figure can be viewed at wileyonlinelibrary.com]

conversion generally, while industrial oil palm concessions account for similar proportions of PSF conversion inside versus outside of concessions.

Our estimate of agricultural extent on peatlands is greater than previously estimated. We found that all industrial plantations combined and smallholder agriculture respectively cover 28% and 23% of the original peatland extent, compared to previous reports of 15%–20% (Miettinen & Liew, 2010a; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016) and 17.8% (Miettinen & Liew, 2010a) cover. Our greater estimates of agricultural extent for South-East Asia are probably attributable to the finer spatial resolution of our data and relatively nuanced visual interpretation of the Landsat imagery. Unlike many previous studies, our estimates also encompass the entire regional peatland extent, including Brunei and southern Thailand, across which conversion rates and agricultural practices vary considerably (Miettinen & Liew, 2010a; Miettinen, Hooijer, Wang, et al., 2012).

3.2 | Future peatland land use

In Indonesia, 53% of current national PSF (45% of the remaining regional PSF extent) is projected to disappear over the next three decades given historic rates of conversion and current land-use plans (Figure 1). Specifically, 28% of remaining Indonesian PSF is within industrial plantation concessions for oil palm and *Acacia*, which may be converted by ~2040, while a further 25% exists outside of all land-use plans (i.e., outside industrial plantation and logging concessions, protected areas, moratorium areas) and may also be converted by ~2040 given the historic smallholder conversion rates outside concessions (Table S1). However, these projections are conservative, particularly given the possibility of smallholder conversion of PSF under the moratorium. Some 42% of remnant Indonesian PSF lies within protected areas and areas covered by the moratorium, which we optimistically presumed to persist indefinitely, and a further 4% lies within logging concessions that legally cannot be converted.

3.3 | Indonesian moratorium

The potential of the Indonesian moratorium on new industrial concessions to influence trajectories of PSF loss and stem resulting emissions is limited despite its extensiveness because of the scale of historic PSF clearance, conversion, concessions, and fragmentation. While the moratorium encompasses 32% of Indonesia's original peatland extent, only 52% of this area is actually PSF (Figure 2). The remaining moratorium area is either agriculture (22%) or nonagricultural mosaic and degraded land covers (27%), both of which continually emit large amounts of CO_2 (Miettinen et al., 2017). Further, a significant proportion of the PSF encompassed by the moratorium is, in addition to being previously legally protected from conversion (Murdiyarso, Dewi, Lawrence, & Seymour, 2011), threatened by passive drainage and peat CO_2 emissions due to the drainage of adjacent agricultural areas. We found that ~40% of PSF under the moratorium is within the critical distance of <1 km (Hooijer et al., 2010, 2012) from existing agriculture as of 2010 (Table 2), where passive drainage and peat CO_2 emissions are probable. This proportion will increase in future with the progressive agricultural conversion inside and outside of concessions. Upon accounting for current land use and passive drainage, 40-48% of the intact PSF in the moratorium area on peatlands is a carbon source, having estimated gross emissions of 0.02–0.05 $GtCO_2$ in 2010 (Table 2).

3.4 | Emissions

Our estimates of gross historic CO_2 emissions during 1990–2010 following peat drainage and agriculture conversion are also higher than previously estimated. We estimate that over 1990–2010, of the 60% of original PSF extent lost, 35% of peatlands underwent agriculture conversion which resulted in emissions of 1.46–6.43 $GtCO_2$ (Table 3), equivalent to 0.3%–1.2% of global CO_2 emissions due to fossil fuels and cement production during the same period (World Bank, 2013). While this is just below the range of 1.3%–3.1% of

TABLE 2 Extent of passively drained peat swamp forest (PSF) within the Indonesian moratorium due to agriculture conversion of peatlands at 1 km and 2 km distance

	Sumatra			Kalimantan			Total		
	km^2	% affected by drainage	$GtCO_2\ ha^{-1}\ yr^{-1}$	km^2	% affected by drainage	$GtCO_2\ ha^{-1}\ yr^{-1}$	km^2	% affected by drainage	$GtCO_2\ ha^{-1}\ yr^{-1}$
Moratorium PSF	11,438	–		19,445	–		30,883	–	
1-km drainage	6,574	57%	0.013–0.023	5,861	30%	0.011–0.020	12,435	40%	0.024–0.043
2-km drainage	7,948	69%	0.015–0.028	6,996	36%	0.014–0.024	14,944	48%	0.029–0.052

TABLE 3 Emissions ($GtCO_2$) due to past and future agricultural conversion inside and outside of concessions on peatlands in Indonesia. The range is the low and high estimates amongst eighteen scenarios for each peatland agriculture type (more info on emissions by land-use type in the Supplementary materials)

	Historic emissions[a]	Future emissions (historic conversion)[b]		Future emissions (future conversion) inside concessions[c]		Future emissions (future conversion) outside land-use plans[d]		Total Future Emissions[e] (historic[b] + future inside[c] + future outside[e])	
	1990–2010	2011–2040	2041–2130	2011–2040	2041–2130	2011–2040	2041–2130	2011–2040	2041–2130
INDONESIA	1.32–5.65	2.01–5.81	2.23–4.93	1.03–2.76	2.37–4.43	0.50–2.58	1.24–5.16	3.54–11.15	5.84–14.52
Kalimantan	0.19–0.84	0.18–0.76	0.14–0.43	0.22–1.05	0.68–1.68	0.10–0.51	0.60–2.71	0.50–2.32	1.42–4.82
Sumatra	1.12–4.80	1.83–5.05	2.09–4.50	0.81–1.71	1.69–2.75	0.40–2.07	0.64–2.45	3.04–8.83	4.42–9.70
MALAYSIA	0.23–1.13	0.75–2.70	0.49–1.73					0.75–2.70	0.49–1.73
East Malaysia	0.08–0.46	0.44–1.51	0.25–0.78					0.44–1.51	0.25–0.78
West Malaysia	0.15–0.67	0.31–1.19	0.24–0.95					0.31–1.19	0.24–0.95
TOTAL	1.55–6.77	2.77–8.51	2.73–6.66	1.03–2.76	2.37–4.43	0.50–2.58	1.24–5.16	4.29–13.86	6.33–16.25

Note. [a]Emissions due to historic conversion to 2010.
[b]These data exclusively reflect the continuation of emissions from peatlands converted prior to 2010.
[c]Emissions due to conversion of PSF within oil palm and Acacia concessions.
[d]Outside land-use plans denote future emissions due to conversion of mature/primary and secondary/regrowth PSF outside of concessions, the Indonesian moratorium area, and protected areas.
[e]Total future emissions" include emissions from historic conversion and from inside and outside concessions. These data are underestimates of likely total future emissions inclusive of future conversion.

global emissions estimated by Hooijer et al. (2010), their calculations incorporated a much larger peatland extent by including nonagricultural degraded peatlands and the Indonesian province of Papua, suggesting that actual total regional peatland emissions are much higher than previously indicated.

Emissions during 1990–2010 varied substantially across South-East Asia. The greatest cumulative emissions arose from Sumatra (1.05–4.54 $GtCO_2$) followed by Malaysia (0.23–1.13 $GtCO_2$) and Kalimantan (0.17–0.77 $GtCO_2$). Annual emission rates from agriculture on peatland nearly doubled over 1990–2000, rising from 0.04–0.17 $GtCO_2$/yr during 1990–2000 to 0.08–0.46 $GtCO_2$/yr during 2000–2005 and to 0.09–0.38 $GtCO_2$/yr during 2005–2010 (Figure 3 S1). This increase was driven mainly by a 116%–130% increase in emissions from Sumatra, rising from 0.03–0.12 $GtCO_2$/yr during 1990–2000 to 0.07–0.26 $GtCO_2$/yr during 2005–2010, reflecting a significant recent expansion of industrial oil palm plantations and smallholders (Tables 1, S1).

CO_2 emissions will continue rising and remain globally significant given historic and future land-use change despite the Indonesian moratorium and similar extraconcession conservation initiatives. Committed emissions from peatlands converted to agriculture prior to 2010 account for 58%–62% (2.48–7.43 $GtCO_2$) and 33%–38% (1.95–4.02 $GtCO_2$) of projected gross future peatland emissions for 2011–2040 and 2041–2130, respectively (Figure 3, S1, Table 3). Projected future emissions due to the conversion of all unprotected, nonmoratorium peatlands between 2011 and 2040 will release similar emissions inside (1.02–2.75 $GtCO_2$) and outside concessions (0.48–2.53 $GtCO_2$). Similar comparable emissions will continue over 2040–2130 inside (2.24–4.06 $GtCO_2$) and outside of current concessions (1.01–4.24 $GtCO_2$) (Table 3). By 2130, all regional peatlands would completely vanish given current conversion rates, and CO_2 emissions would reduce considerably. Total emissions from peatlands between 2011 and 2040 will be equivalent to 0.7%–2.3% of global fossil fuel and cement emissions between 1990 and 2010 and to 0.9%–2.2% between 2041 and 2130. The effective enforcement of recent Indonesian policy towards peatland restoration might result in actual emissions following some of our lower projections.

4 | DISCUSSION

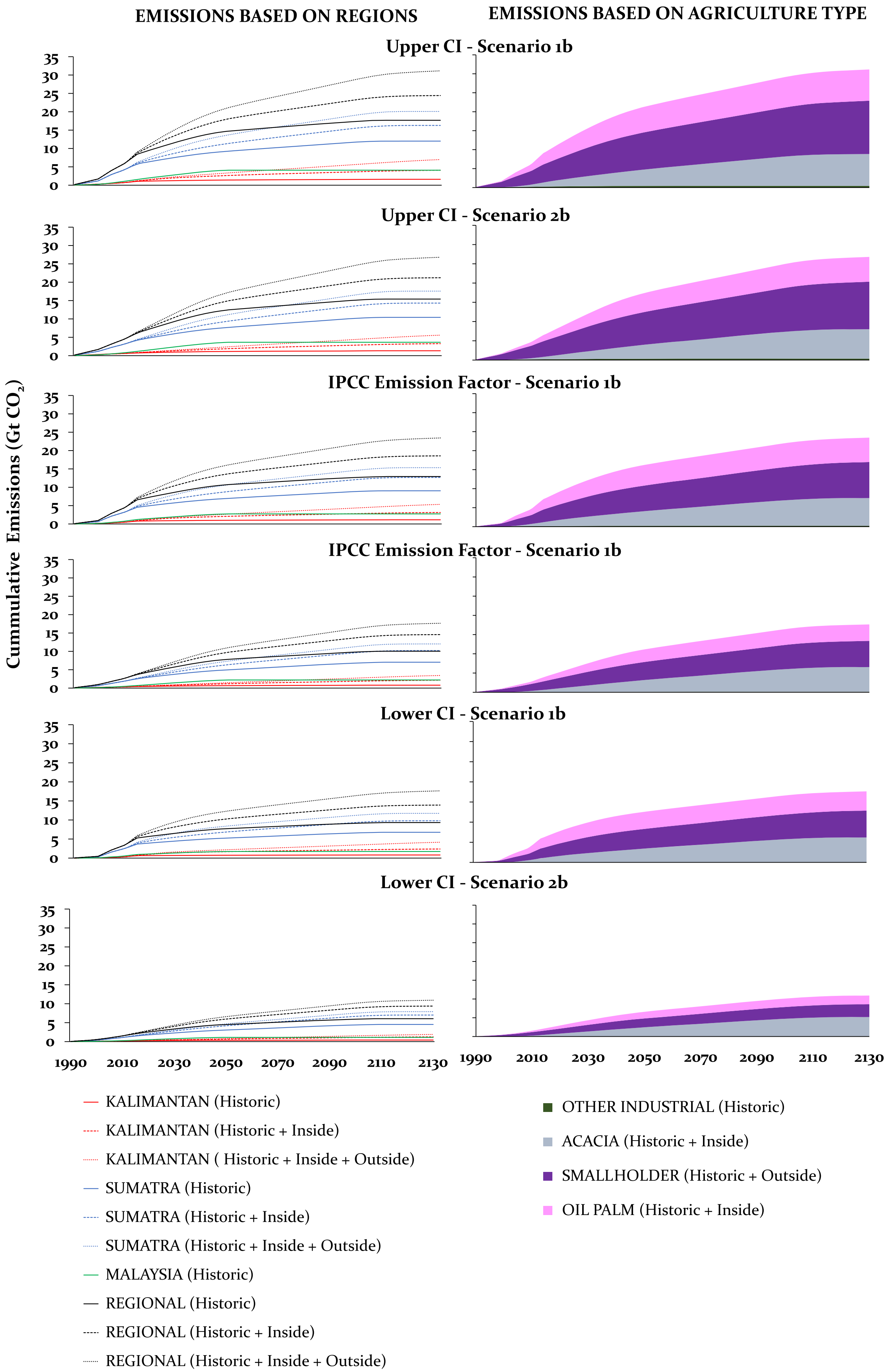
Reducing emissions from peatlands caused by the legacy of extensive historical disturbances is complicated due to multiple interacting factors (Figure S2). Land-use planning and legislation that cover entire peat domes are important, as peatlands are made up of hydrological units and effective long-term management requires that the hydrological units are managed holistically. For example, partial drainage of a unit, due to agriculture, will entail negative hydrological impacts up to 2 or 3 km into adjacent areas of forest being managed for conservation (Hooijer et al., 2010). While recent legislation has acknowledged the importance of hydrological units and the need for land-use planning in peatland management, it remains extremely difficult to apply this legislation across landscapes with multiple stakeholders, often unclear land use tenure, and multiple agencies and levels of government (President of Indonesia, 2014a, 2016). An alternative to the unrealistic option of using legislation to rehabilitate areas already under agriculture is to develop alternative nondrainage-based agriculture, which in theory would have much lower or negligible emissions (Wijedasa et al., 2016). There is, therefore, a demonstrable requirement for clear leadership and for effective enforcement and adequate finance.

The major factors determining peatland emissions outlined here lead to four recommendations to meaningfully reduce future emissions: (1) conserve PSF inside concessions via greater cooperation with agribusiness, (2) conserve PSF inside protected areas via enhanced enforcement, (3) conserve PSF outside of all known land-use plans via clarification of land-use status and tenure to allow enforcement of legislation, and (4) encourage the development of low emissions or CO_2 neutral land uses (e.g., nondrainage-based agriculture, silviculture) on land formerly converted from PSF.

First, the extent of peatland for which emissions' reductions are potentially most readily achievable is the 28% (20,230 km^2) of remaining Indonesian PSF within plantation concessions. If converted to agriculture, this PSF would release 23%–26% (1.02–2.75 $GtCO_2$) of projected gross emissions between 2011 and 2040 (Table 3). Arguably, this realm of PSF is currently the best protected, or at least the most amenable to enhanced protection, as it has secure land tenure (i.e., it lies within government-designated concessions), established company infrastructure and monitoring, financing, often zero-deforestation pledges by larger companies, and public scrutiny of company actions to discourage illegal corporate and smallholder conversion. Crucially, some of these PSFs are already independently and voluntarily protected and managed by plantation companies as high conservation value (HCV) and high carbon stock (HCS) forests (APP, 2013; APRIL, 2015; Greenomics Indonesia, 2014; Greenpeace UK, 2015). For instance, the two companies with the largest extent of peatland concessions in Indonesia, APP and APRIL, have committed to conserve the remaining natural forest within their concessions (APP, 2013; APRIL, 2015). This independent corporate protection of PSF has also prevented smallholder encroachment of official protected areas in Sumatra, such as the Kampar Peninsular, Kerumutan, Giak Siak Kechil-Bukit Batu, and the south of Berbak National Park. In some cases, plantation companies have gone a step further by obtaining PSF ecosystem restoration licences enabling them to manage and restore logged protected forests within their landscapes, such as the Riau Ecosystem Restoration Concession, the Giam Siak Kechil Man and the Biosphere Reserve, and the Katingan Ecosystem Restoration Concession (Ceruti, 2016; Indriatmoko, Atmadja, Utomo, Ekaputri, & Komarudin, 2014). Together, these three concessions cover three of the largest and most intact PSF hydrological units in Indonesia. In this light, there exists an opportunity for national legislation to build on these independent corporate initiatives and extend formal PSF conservation across much larger areas of PSF within current concessions.

However, PSFs within concessions still face three major uncertainties. First, a 2014 revision to the Indonesian Plantation Act stipulates that agriculture concessions must be fully converted to the intended land use within 6 years of the licence date under penalty of forfeiture (Butler, 2014; Greenomics Indonesia, 2014; President of Indonesia, 2014b), seemingly contrary to the corporate initiatives noted above. Second, many smaller, domestic oil palm companies have not adopted conservation pledges but rather have earmarked large areas of PSF for conversion via legally sanctioned protocols. In Indonesia, such concessions are typically granted in large part by district and provincial-level governments, the land-use plans of which are no longer subject to amendment by the central government, legally or practically (Sloan et al., in review; McCarthy & Robinson, 2016). Third, major agriculture concessionaires have expressed agreement in principal with new government legislation which would enable "land swaps" between PSF in concessions zoned for conservation with degraded forest elsewhere (preferably on mineral soils) (Butler, 2013, April 19; Minister of Environment and Forestry, 2017a). So, too, has the Indonesian Ministry of Environment and Forestry whose recent peatland conservation initiatives render some plantations, on peat of 3m or greater depth or identified for conservation, unsuitable for cultivation (Government of Indonesia, 2016; Minister of Environment and Forestry, 2017b, 2017c, 2017d). Such land swaps—ostensibly supportive of PSF conservation, particularly where PSF is earmarked for conversion—also have the potential to

FIGURE 3 Cumulative CO_2 emissions under six emission scenarios due to historic (1990–2010) peatland conversion in Malaysia, Sumatra, and Borneo with future projections until 2130 based on agricultural conversion of unprotected peat swamp forest. REGIONAL denotes emissions from Malaysia, Brunei, Thailand, Sumatra, and Borneo. HISTORIC denotes emissions due to historical peatland conversion over 1990–2010. INSIDE denotes future emissions due to conversion of mature/primary and secondary/regrowth PSF inside concessions. OUTSIDE denotes future emissions due to conversion of mature/primary and secondary/regrowth PSF outside of concessions, moratorium, and protected areas. Emission scenarios are outlined in the supplementary methods (Table S8) [Colour figure can be viewed at wileyonlinelibrary.com]


EMISSIONS BASED ON REGIONS
EMISSIONS BASED ON AGRICULTURE TYPE
Upper CI - Scenario 1b
Upper CI - Scenario 2b
IPCC Emission Factor - Scenario 1b
IPCC Emission Factor - Scenario 1b
Lower CI - Scenario 1b
Lower CI - Scenario 2b
Cummulative Emissions (Gt CO2)
0 5 10 15 20 25 30 35
1990 2010 2030 2050 2070 2090 2110 2130
KALIMANTAN (Historic)
KALIMANTAN (Historic + Inside)
KALIMANTAN (Historic + Inside + Outside)
SUMATRA (Historic)
SUMATRA (Historic + Inside)
SUMATRA (Historic + Inside + Outside)
MALAYSIA (Historic)
REGIONAL (Historic)
REGIONAL (Historic + Inside)
REGIONAL (Historic + Inside + Outside)
OTHER INDUSTRIAL (Historic)
ACACIA (Historic + Inside)
SMALLHOLDER (Historic + Outside)
OIL PALM (Historic + Inside)

diminish current protections by removing plantation land tenure and corporate vigilance. This, in turn, could render currently intact peatlands vulnerable to smallholder agricultural expansion. Successful PSF conservation within concessions will ultimately depend heavily on the security of the conservation pledges made by larger concession companies, as well as on similar initiatives being adopted more widely by smaller companies. A current, temporary "freeze" on Indonesian PSF conversion within concessions pending the clarification of the extent of forest designated for conversion may provide an opportune window in which to promote such a PSF conservation initiative (Alisjahbana & Busch, 2017; Government of Indonesia, 2016).

The second initiative to reduce peatland emissions is to enhance the protection of existing protected areas; this would complement enhanced corporate-driven PSF conservation, as discussed above. While we did not quantify PSF conversion or emissions from protected areas alone, conversion inside protected areas is doubtless significant and is dominated by smallholder agriculture which results in both active and passive drainage and emissions. The Indonesian government has recently acknowledged that removing existing smallholder agriculturalists from its protected areas is not feasible; it will, instead, allow them to remain, provided that there is no further encroachment (Jong, 2018). However, preventing future encroachment will require resources (manpower and finance) in support of successful implementation measures and it therefore remains highly uncertain whether Indonesia can minimize emissions arising from encroachment into protected peatland areas (Brun et al., 2015; Gaveau et al., 2009; Miettinen, Wang et al., 2013).

Third, more generally, conservation may be expanded to the PSF outside of concessions and the land-use plans considered here. Such expanded conservation could encompass the 25% (18,650 km^2) of Indonesian PSF situated outside of protected areas, the moratorium area, and agricultural and logging concessions. Conserving this realm of PSF would prevent 12%–22% (0.48–2.53 $GtCO_2$) of anticipated gross emissions between 2011 and 2040, or more if accounting for the prevention of future passive PSF drainage. However, land-use planning and enforcement of legislation of these areas are hindered by uncertainty in land-use tenure. While some form of local government land tenure or informal local community claims (known as adats) may exist for these lands, they are not reflected on government zoning maps. An attempt to bring these maps together into a single map known as OneMap began a few years ago; however, it is yet to show any results (Alisjahbana & Busch, 2017; McCarthy & Robinson, 2016). If this single map does materialize, it would allow enforcement of existing peatland laws to these lands, without which it is possible that smallholder conversions of these areas may occur.

Fourth, as peatlands converted to agricultural use prior to 2010 will contribute 58%–62% (2.48–7.43 $GtCO_2$) of future emissions to 2040 and are arguably under permanent cultivation for the foreseeable future, developing agricultural techniques tolerant of high water tables where there is a reduced (or ideally no) net loss of CO_2 should be a regional priority (Wijedasa et al., 2016). Indeed, in 2016 and 2017, Indonesia enacted reforms stipulating average peat water table depths of 40 cm within active concessions, provoking major anxieties from agribusinesses but uncertain implications to date (Alisjahbana & Busch, 2017; Government of Indonesia, 2016; Minister of Environment and Forestry, 2017b, 2017c, 2017d). Companies have the finance, infrastructure, and knowledge to start developing such techniques, which could be trialled in peatland restoration and alternative species trial sites. Techniques relevant to smaller agricultural production should not be overlooked, however. Current agriculture on wet peatlands or "paludiculture" is unproductive and largely untested, in terms of both potential crops and markets (Giesen, 2015). In the interim, maintaining higher water tables under existing agricultural uses would reduce peat CO_2 emission rates and enhance the long-term sustainability of peatland agriculture, given that the rapid oxidation of drained peat leads to peatland subsidence and ultimately to inundation prohibitive of cultivation (Hooijer et al., 2010, 2012). The contribution of paludiculture techniques to future emission reduction is relatively uncertain but probably substantial.

Collectively, between 2011 and 2040, conservation of PSF inside concessions, conservation of PSF outside of known concessions and protected areas, and developing alternative high water table agricultural techniques could prevent future peatland emissions equivalent to 0.7%–2.3% of global fossil fuel and cement emissions between 1990 and 2010. These priorities entail relatively direct and difficult "on-the-ground" engagements with the drivers of PSF loss compared to current passive and potential future REDD+ strategies, including the moratorium.

Our findings on the role of smallholder farmers question the positions and related narratives prominent amongst conservationists that government-sanctioned corporate industrial plantations are chiefly responsible for PSF loss (Abood et al., 2014; Koh et al., 2011; Lee et al., 2014; Miettinen, Hooijer, Shi et al., 2012; Miettinen et al., 2016). The findings instead recommend a more diversified conservation approach sensitive to smallholder dynamics and community forest management, including their interactions with industrial plantations (Sloan, Locatelli, Wooster, & Gaveau, 2017). Recent severe haze events driven by peat fires in South-East Asia, particularly the 2015 El-Niño related haze (Chisholm et al., 2016; Wijedasa et al., 2015), have provided the impetus for significant land-use reform which could reduce drainage, conversion, and related emissions. The Indonesian Peat Restoration Agency, responsible directly to the president, was established in January 2016 with the mandate to restore two million hectares of fire-affected peatlands (President of Indonesia, 2016). Recent legislation also affords this agency the power to identify PSF hydrological units and to prescribe land-use plans to maintain hydrological integrity (Minister of Environment and Forestry, 2017c; President of Indonesia, 2014a). Such powers include the ability to protect PSF and to rewet converted peatlands to avoid significant carbon emissions from drainage and fires (Minister of Environment and Forestry, 2017d, 2017e). This is consistent with the recent legislation requiring companies to raise water tables in agricultural areas as well as to rewet and restore peatlands currently under plantation cultivation (Minister of Environment and Forestry, 2017b). Collectively, the Peat Restoration Agency and the current policy and legislative framework could provide a route to meaningfully stem regional PSF loss and emissions and comply with regional emission-reduction commitments buoyed by the recent global COP21 Paris Accord. Achieving the policy and legislative goals will, however, require enhanced long-term financing and commitment to the science, the means, and the politics of peatland restoration and alternative agriculture.

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AUTHOR CONTRIBUTIONS

L.S.W., S.S., G.R.C., and T.A.E. conceived and designed the experiments; L.S.W. performed the experiments; L.S.W. and S.S. analysed the data; L.S.W., S.S., G.R.C., L.M, S.E.P., and T.A.E. co-wrote the manuscript.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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